

ON SIDERITE AND ASSOCIATED MINERALS FROM THE COLUMBIA RIVER BASALT AT SPOKANE, WASHINGTON.

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INTRODUCTION.

Some years ago Mr. Henry Fair, of Spokane, Washington, noted that the rock of the Columbia River lava flows being excavated in the city of Spokane contained vesicular cavities in which were developed unusual minerals, most abundant and conspicuous among which was siderite in the peculiar spherical forms commonly called sphaerosiderite. Mr. Fair carefully selected a large collection of the best of the specimens of this material for preservation in the Eastern Washington State Museum and a number of duplicates was sent to the New York Mineralogical Club for distribution among the members. One specimen from this lot was sent to the National Museum by L. P. Gratacap. An analysis of the siderite having been made by J. P. Maider, city chemist of Spokane, the optical properties were measured by Larsen and the data published by Wherry and Larsen.¹ These results have since been again used by Gaubert.²

Mr. Fair has desired that the material be given a more general and detailed study and that, if of sufficiently general interest, the results be published. To this end he recently donated a representative series of specimens from the locality to the National Museum. These have been studied in the Museum laboratory, with results as below.

The minerals identified include feldspar (oligoclase-andesine), magnetite, cristobalite, siderite, pyrite, iron opal, hyalite, calcite, aragonite, barite, limonite, and goethite. One of the most interesting though least conspicuous of these is the cristobalite, which occurs in well-formed crystals which it has been possible to measure on the goniometer. The paragenesis and association of the minerals of the

¹ Edgar T. Wherry and Esper S. Larsen. The indices of refraction of analyzed rhodochrosite and siderite. Journ. Wash. Acad. Sci., vol. 7, pp. 365-368, 1917.

² P. Gaubert. The indices of refraction of the rhombohedral carbonates. Bull. Soc. Franc. Min., vol. 42, pp. 88-120, 1919.

cavities are subjects of some interest, especially since the minerals of the vesicular cavities of the basalt of this great area have heretofore been given little attention.

Grateful acknowledgment is due Mr. Fair for his part in discovering and making available the materials for study and in furnishing information relative to their occurrence. With the single exception of the cristobalite all of the minerals mentioned were correctly identified by their collector.

As a preliminary to the description of the minerals of the basalts it is considered pertinent to offer a summary of available information relative to this great area of lava flows known collectively as the Columbia River Basalt Plateau.

THE COLUMBIA RIVER BASALT.³

The Columbia Basalt area, including the Snake River lava of Idaho, forms one of the greatest lava regions of the world, being comparable only to the Dekkan Traps of India, which cover about the same area and have a similar composition and many other fea-

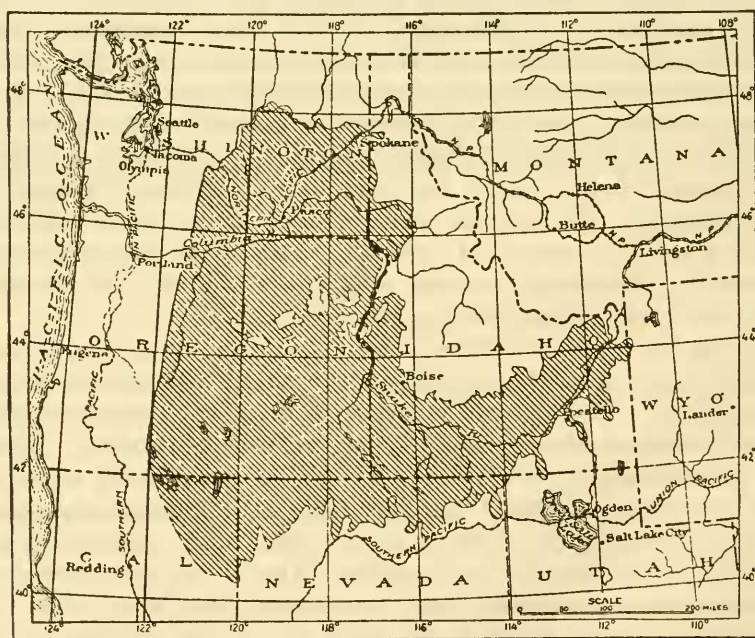


FIG. 1.—SHOWING APPROXIMATE EXTENT OF COLUMBIA RIVER BASALT AREA. (AFTER CAMPBELL. U. S. GEOLOGICAL SURVEY BULLETIN 611.)

tures in common. The total area covered by the lavas has been variously estimated as from 200,000 (518,000 square kilometers) to 250,000 square miles (648,000 square kilometers), and includes the

³ This account and the accompanying figure 1 taken from M. R. Campbell. U. S. Geological Survey Bulletin 611, pp. 165-166, 1915.

greater part of Washington, all of eastern Oregon, much of northern California, and the great expanse of the Snake River Plain in Idaho. The approximate extent of the lava fields is shown in the accompanying map (fig. 1).

It is generally believed that the lava was poured out of open fissures and, being exceedingly fluid, spread widely in thin level sheets. This idea is based upon several lines of evidence: First, the volume and extent of the lava are so great that it is difficult to conceive their eruption from ordinary craters. Second, the rarity of the fragmental materials known as tuffs, breccias, etc., indicates a welling up through fissures without the explosive action characteristic of crater eruptions. Third, old fissures through which the floods of lava came forth have been discovered, fissures now filled with cooled and hardened basalt in observable connection with the overlying sheets of lava.

The basalt area is not a single flow but rather a complex of numerous relatively thin flows, the whole reaching in places a thickness of thousands of feet. About 20 separate flows are exposed in bluffs of the Columbia River. Each one represents a distinct outpouring of lava, the eruptions being separated by long periods of time, some of which must have endured for centuries, for they are marked by beds of soil in which trees grew to considerable size before being charred and buried by later flows. The eruptions of lava, especially in the later stages of activity, were separated also by periods in which other materials accumulated, consisting of volcanic ash and beds of sand, clay, and gravel laid down in lakes and rivers.

In addition to the massive flows that constitute the greater part of the material there are beds of fragmental volcanic material, such as bombs and smaller angular fragments of lava. Such materials have either been thrown up to great heights and rained down upon the surrounding country or, mixed with hot water, have flowed over the surface as mud. The fragmental materials are not as widely distributed as the massive flows.

The quantity of material poured out during this period was enormous. The greatest thickness of the lava and associated deposits is not less than 4,000 feet (1.25 kilometers), but if it averages only 500 feet (0.15 kilometer) over its entire area, seemingly a very moderate estimate, it would make a mass of 24,000 cubic miles (100,000 cubic kilometers) or a cube nearly 30 miles (48 kilometers) in height. Even this great volume may be far less than was actually poured out.

GEOLOGY OF THE CITY OF SPOKANE.

The geology of the city of Spokane has not been mapped in detail, although many geologists have worked in the surrounding territory and have examined the rocks in the city casually. The basalt is

exposed in many places in street and railway cuttings and it is from these exposures that the minerals described below have come. At Division Street and Mallon Avenue, which are shown in the photographs reproduced as Plate 1, two distinct flows of basalt are exposed. At the point marked (x) at the right of the lower picture there was found between the flows a portion of a tree trunk 10 feet (3 meters) in diameter and 5 feet (1.5 meters) long, charred at one end. Dr. Frank H. Knowlton identified this wood as belonging to the genus *Sequoia* but of undeterminable species. The wood is dark, hard, and somewhat brittle, resembling ebony more than redwood, but it is so well preserved that the log was sawed into boards which were made into a box. Although some coaly material may be seen in the pores, the wood is not conspicuously lignitized. Spokane is practically at the eastern limit of the basalt area and the lava here is relatively thin, and hills of older rocks project through it in places. The very fluid material filled the floor of Spokane Valley extending up to Coeur d'Alene Lake and for many miles up the tributary Coeur d'Alene and St. Joe Valleys, giving these tortuous canyons a level floor of solid stone. This has been cut through by later erosion, and the basalt remains as flat topped terraces along the valley sides.

Mr. Fair reports that certain wells sunk in the city of Spokane have penetrated 264 feet (80 meters) of basalt and 286 feet (87 meters) of silt and have been drilling for 500 feet (152 meters) in granite in search of oil. The silt which underlies the basalt is apparently a lake deposit formed in water ponded by damming of the Spokane Valley by earlier flows of the lava and covered by the later flows. It has been found to contain abundant plant remains which are of Upper Miocene age.

The rock of the flows in Spokane varies from spongy material, in which half the volume is occupied by irregular open cavities, to dense compact granular basalt which shows typical columnar structure. In places the material from surfaces of flows is glassy, forming a basaltic obsidian, and there are occasionally inclusions of mud.

PETROGRAPHY OF THE BASALTIC ROCKS.

The specimens of Spokane basalts submitted to the writer for examination are varied in appearance, but those which enclose the vesicles containing minerals are all of two major varieties characterized as light and dark basalt by Mr. Fair. Both of these are equigranular moderately fine-grained holocrystalline rocks. The light-colored variety is light gray in color and granular in structure with a harsh lusterless surface on fresh fracture. It is perfectly fresh with no sign of alteration. As contrasted with this the dark-colored variety has a dark greenish brown color, greasy luster, and dense conchoidal fracture. In thin section under the micro-

scope the fresh gray rock of the light variety is seen to be a normal basalt consisting of twinned laths of plagioclase in a mesh of perfectly fresh augite, the texture being typically ophitic, although some of the pyroxene grains have a tendency to euhedral development. Large euhedra of iron ore are scattered throughout the section, and there occurs interstitially a moderate amount of brownish glass filled with minute acicular microlites.

The sections of the dark rock show only one essential difference from those of the light rock. This dark rock is composed of the same perfectly fresh assemblage of plagioclase, which by its extinction angles is shown to be bytownite, with augite and accessory iron ore and glass. Throughout the rock, however, there are interstitial areas of a transparent yellow-brown isotropic material having an index of refraction of 1.432 to 1.438, which is evidently opal colored by hydrated ferric oxide. The opal occupies the same relative position as the glass with relation to the other constituents, and it may represent an alteration product or replacement of the glass. That this material is not merely glass stained by iron is shown by its much lower index of refraction. The microlites which are present in the glass do not occur in the opal. The other constituents of the rock are free from any sign of alteration or staining, and areas of glass which still remain in the sections which contain the opal show no incipient or partial replacement by the opal.

THE VESICULAR CAVITIES.

The cavities are varied in size from minute to some which are 15 cm. or more in diameter. They are most abundant in the more glassy forms of the basalt, but the larger ones are in the dense crystalline rocks. Many of these vesicles are nearly spherical and represent typical gas bubbles, while others are much flattened and deformed as though by movement after the enclosing lava had become very viscid. It is with the several minerals which occur in these cavities that this paper has chiefly to do. These are described in some detail below, even though the majority of them are not particularly rare or remarkable species. The minerals are, with one or two exceptions, discussed essentially in the order of their deposition.

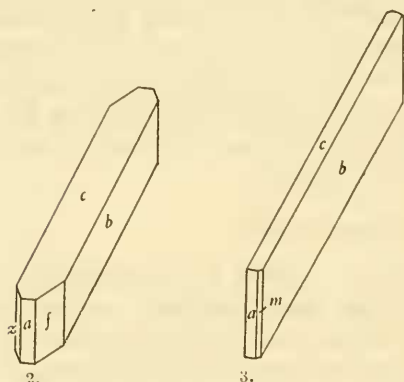
PLAGIOCLASE (OLIGOCLASE-ANDESINE).

The first lining of the vesicles of the freshest rock is composed either of a grayish glassy enamel-like coating or of a crust of distinctly lath-like crystals of plagioclase. The largest of these feldspar crystals reach 2 mm. in length. Upon microscopic examination the gray glaze is found, like the crystals, to consist of feldspar, there being no isotropic material present in the enamel. Every gradation exists between the gray enamel and the crystal crusts, intermediate

forms appearing like crystals which had partly fused. The lowest index of refraction of the feldspar, a , is 1.5400, and this together with its extinction angles identify it as oligoclase-andesine as contrasted with the much more basic bytownite of the enclosing basalt. One rather imperfect crystal which was measured on the goniometer had the habit shown in figure 2, the forms identified being as shown, c (001), b (010), a (100), f (130), and z ($\bar{1}30$). Another common form is shown in figure 3. While the combinations are simple, the crystals vary widely in proportions, ranging from slender acicular by elongation on axis a to very broad and thin tabular to the pinacoid b (010). Twins on b (010) are common (albite law), and a crystal twinned on c (001) was seen (Manebach law).

MAGNETITE.

Magnetite is invariably present as minute sharp and brilliant crystals interspersed with the lath-like crystals of plagioclase in the cavities. The crystals are always simple octahedrons, often with depressed faces, as shown in figure 4. The most noteworthy thing about the minute magnetite crystals is their tendency to align themselves in strings in parallel position, as shown in figure 5.



FIGS. 2-3.—COMMON HABITS OF PLAGIOCLASE CRYSTALS FROM BASALT.

CRISTOBALITE.⁴

Cristobalite, the pseudoisometric form of silica, was first named by G. vom Rath⁵ from material from Cerro de San Cristobal, Hidalgo, Mexico, where it occurs as octahedral crystals up to 2 mm. in size and as spinel twins up to 4 mm. in diameter associated with tridymite, hornblende, and hematite in cavities in augite andesite. Although giving the form a new name, vom Rath himself was inclined to believe it to be either pseudomorphous after some isometric mineral, such as spinel, or to be merely a form of tridymite which had assumed a pseudoisometric form by twinning. Indeed he had previously described in detail cuboctahedral forms of "tridymite" from New Zealand, which, as discussed below, were doubtless cristobalite. The same writer also identified as cristobalite a mineral from the lava from Ettringen described by Wolf⁶ and by Lehmann⁷ as druses with

⁴A preliminary note on the cristobalite has been published. Earl V. Shannon. Journ. Wash. Acad. Sci., vol. 12, pp. 195-196, 1922.

⁵G. vom Rath, N. Jahrbuch, 1887, pt. 1, p. 198.

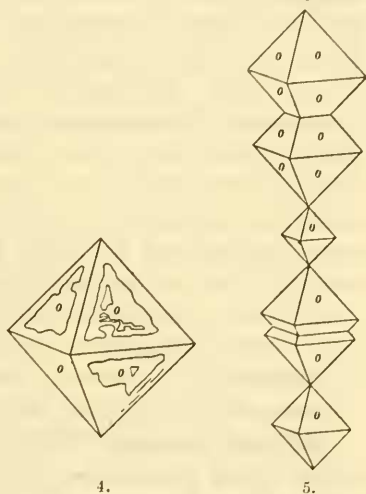
⁶Th. Wolf, Zeits. der Geol. Gesellsch., 1869, vol. 20, p. 16.

⁷J. Lehmann. Ver. Nat.-List. Ver. Rheinl., Bonn, 1874, p. 35.

white or yellowish octahedrons and spinel twins. Lacroix⁸ found cristobalite with quartz and tridymite in cavities in the basaltic rock from Mayen, and Gaubert⁹ found one-half mm. cristobalites in lavas from Mayen and Niedermendig. Lacroix¹⁰ found cristobalite octahedrons with tridymite in volcanic blocks from the St. Vincent eruption of 1902-3.

Cohen¹¹ has reported cristobalite with carbon and schreibersite, as sharp crystals 0.01 to 0.09 mm. in size, showing the cube either alone or with the octahedron, in the meteoric iron of Kendall County, Texas. Aside from this occurrence in meteoric iron, which must be considered as requiring confirmation, the first recognition of the occurrence of this mineral in the United States was by Rogers,¹² who identified cristobalite in volcanic rocks from two localities in California and associated with orthoclase rods in spherulites in obsidian from Yellowstone National Park.¹³ The latter cristobalite is fairly abundant in spherical aggregates 0.3 mm. in diameter and is subtranslucent with an enamel-like appearance. Under the microscope it is faintly birefringent, with a complicated mosaic structure, and shows polysynthetic twinning in spots. The refractive index is 1.485 ± 0.005 . Upon heating, the mineral became translucent and upon cooling reverted again to the subtranslucent form. Later Rogers has mentioned still a third California locality for this mineral.¹⁴

While the earlier authors were inclined to regard cristobalite as either a pseudomorph after an isometric mineral or as a mimeoisometric aggregate of twinned tridymite crystals, the mineral is now regarded as a well-substantiated species. Its synthesis has been effected by several investigators, and the results of Fenner,¹⁵ being the most recent and complete, may be summarized here. In general silica heated with a flux (either sodium tungstate or alkaline



FIGS. 4-5.—MAGNETITE FROM BASALT CAVITIES. 4, COMMON OCTAHEDRAL FORM SHOWING DEPRESSED FACES. 5, SHOWING A NUMBER OF OCTAHEDRONS ALIGNED IN PARALLEL POSITION.

⁸ Albert Lacroix. *Bull. Soc. Min., Paris*, 1891, vol. 14, p. 185.

⁹ P. Gaubert. *Bull. Soc. Min., Paris*, 1904, vol. 27, p. 242.

¹⁰ Albert Lacroix. *Bull. Soc. Min., Paris*, 1905, vol. 28, p. 59.

¹¹ Ann. Naturhist. Hofmus. Wien., 1900, vol. 15, p. 385.

¹² Austin Flint Rogers. *Amer. Journ. Sci.*, vol. 45, p. 222, 1918.

¹³ Austin Flint Rogers. *Amer. Mineral.*, vol. 6, p. 4, 1921.

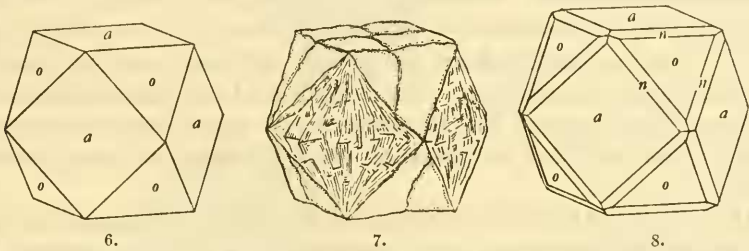
¹⁴ Austin Flint Rogers. *Amer. Mineral.*, vol. 6, p. 60, 1921.

¹⁵ Clarence N. Fenner. The stability relations of the silica minerals. *Amer. Journ. Sci.*, vol. 30, 1913, p. 331.

silicate glass was used) crystallizes as quartz below 870° . Although quartz is the stable form below this temperature, either amorphous silica or cristobalite changes first to tridymite and then to quartz only after much longer heating. Between 870° and $1,470^{\circ}$ tridymite is always formed in a tungstate melt. Within the tridymite range amorphous silica heated in fused sodium tungstate or alkali silicate yields at first a mixture of cristobalite and tridymite, which later becomes entirely converted to tridymite. From $1,475^{\circ}$ upward any form of silica heated in a tungstate melt is changed to cristobalite. Heated without a flux quartz is changed to cristobalite, while quartz and tridymite are never formed in the absence of a flux. In addition to these inversions, which are marked by a complete change of crystalline form and which take place slowly and with difficulty, there is another class of inversions of different character which take place with no notable change in the outer form of the mineral. Cristobalite is isometric in form but is always feebly birefringent and uniaxial optically. The isometric form is stable only at an elevated temperature and inverts upon cooling to the double-refracting pseudoisometric form. These are known as α - and β -cristobalite, respectively. Thus an ordinary birefracting crystal of α -cristobalite heated to a moderate temperature, 300° or slightly less, becomes converted to more transparent isotropic β -cristobalite, which on cooling reverts again to the birefracting α -cristobalite. The variability of the temperature at which this inversion takes place has been discussed in the paper cited and need not be gone into here. The optical and physical properties conclusively isolate cristobalite from the other modifications of the compound SiO_2 .

In those specimens of light-colored nonopalized rock from Spokane which show plagioclase crusts or coatings of the gray enamellike feldspar there occur, associated with the octahedrons of magnetite and attached to the plagioclase or the gray glaze, small whitish crystals or rounded bodies of a porcellanous white mineral agreeing in appearance with the cristobalites described by Rogers. When boiled in hydrochloric acid, these show no tendency to dissolve. This mineral, which had provisionally been called analcite by Mr. Fair, was examined optically by Mr. A. Rodolfo Martinez in this laboratory and found to agree with cristobalite in optical properties, its mean refractive index being 1.485 ± 0.003 . The mineral occurs in whitish crystals averaging 0.5 mm. in diameter, which under a binocular microscope were seen to vary from simple forms to almost spherulitic bodies. In some ways the least simple of these resemble complex penetration twins which could not be interpreted. Occasional crystals, though dull, have the perfect cuboctahedral form shown in figure 6. Most of those which are of this form are also imperfect, and one which was mounted on the goniometer gave no dependable

angles. One face, which was taken as the top cube face (001) and mounted as polar, was found to be depressed and concave and to be divided into four sectors by irregular sutures which yielded four major and numerous minor signals. The octahedral faces were bright enough to reflect, but each of these was found to consist of two or more areas yielding separate signals. The measurements were entirely unsatisfactory, and the vertical faces of the cube were apparently composed of numerous projecting points with shallow reentrant angles. A sketch of a crystal of this sort is given in figure 7. Such forms grade intermediately between the simple crystals and the spherical forms which are characteristic of this mineral at many localities. An excellent idea of the appearance of the cristobalite under a lens can be gained from the photograph, (pl. 2, left), which shows a small cavity in the basalt containing cristobalite associated with rods of feldspar and globules of first generation siderite, the photograph being enlarged six diameters. The most perfect crystal shown in this photograph was removed and measured on the two-circle goniometer, the results being satisfactory in that they indicated



FIGS. 6-8.—CRISTOBALITE CRYSTALS FROM BASALT. 6, SIMPLE CUBOCTAHEDRON SHOWING FORMS A (100) and o (111). 7, SKETCH OF IMPERFECT CUBOCTAHEDRAL CRYSTAL. 8, CUBOCTAHEDRON WITH EDGES BEVELED BY TRAPEZOHEDRON n (211.)

isometric symmetry conclusively. This crystal, as shown in figure 8, was cuboctahedral, but with the edges beveled by the trapezohedron *n* (211) and with no external indication of any twinning. The following measurements were obtained:

Angles measured on cristobalite crystal, figure 5.

No.	Form.	Signal.	Measured.		Calculated.	
			φ	ρ	φ	ρ
			° /	° /	° /	° /
1	c 001	Fair.....	0 00	0 00		0 00
2	o 111	Poor.....	44 17	53 16	45 00	54 44
3	o 111	Fair.....	44 36	54 28	45 00	54 44
4	o 111	Fair.....	45 20	54 28	45 00	54 44
5	o 111	Poor.....	44 18	54 28	45 00	54 44
6	c 100	Good.....	90 00	90 00	90 00	90 00
7	n 211?	Very narrow, no signal.....	44 40	1 29 20	45 00	35 16

¹ Measurement obviously erroneous. Indices established by zonal relations.

Although cristobalite is described as twinning frequently on the spinel law, no spinel twins were found in the Spokane material. The more complex forms of the Spokane cristobalite look so like repeatedly twinned tridymite crystals that, were it not for the unavoidable evidence of the optical properties, one might be tempted to follow vom Rath's earlier example and endeavor to interpret them as twinned tridymite. Previous to his assigning the name cristobalite vom Rath had described apparently isometric silica crystals from New Zealand, which had almost identically the habit of those from Spokane. The occurrence is at Littleton Harbor, near Christchurch in Canterbury, New Zealand.¹⁶ Here a highly crystalline grayish-white layer between beds of basaltic andesite contains vesicles which are invariably lined with a crust of 2 mm. tridymite crystals, sometimes with some quartz. The writer states that some of the crystals in part appear isometric with the cube and octahedron in equal development. Occasionally these show skeleton structure, and they appear to grade into ordinary aggregates of twinned plates of tridymite. The pseudoisometric form is explained as twinning of tridymite on r (3034) combined with trilling on q (1016). It is obvious that these cuboctahedral crystals of vom Rath are entirely similar to those in the Spokane specimens, although no tridymite has been found in the latter. The complicated and improbable explanation of the origin of the isometric forms is no longer necessary in view of the fact that an isometric form of silica has been proven to exist.

It is obvious that in the vesicles of the Spokane basalts the cristobalite, like the plagioclase and magnetite, is a high-temperature mineral deposited during the period immediately following consolidation of the inclosing rock. This need not necessarily indicate, however, that its formation took place at a temperature above 1,470°, as might be inferred from Fenner's work on dry melts, as abstracted above. The presence of volatile constituents in the vesicular cavities, during formation of the minerals forming the crust, may have greatly altered the physical requirements for their crystallization.

PYRITE.

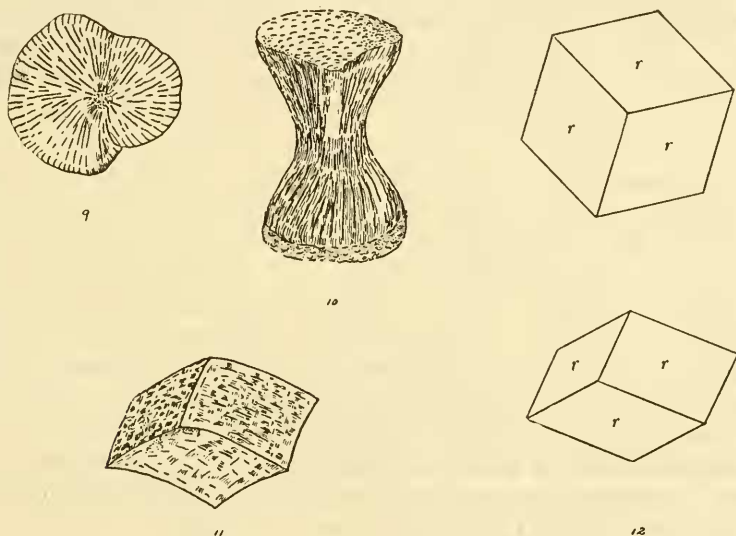
Pyrite was seen to occur sparingly in several specimens and in moderate abundance in one. Aside from recording its presence and position with reference to the other minerals it does not require special description. It is confined to the nonopalized rock and forms thin coatings over the feldspar or feldspar-enamel crusts. In age it is later apparently than the first generation of sphaerosiderite and earlier than the iron opal. In the specimen showing it most abundantly the pyrite coated the gray feldspar glaze completely in places and

¹⁶ G. vom Rath. *Zeitschrift Karystallographie*, vol. 13, p. 599.

occurred as isolated patches on the siderite spheres. Apparently the tendency was toward selective deposition on the feldspar in preference to the siderite. The pyrite forms mossy coatings which show no evidences of crystal form. It commonly shows a deep bronzy tarnish.

SIDERITE (SPHAEROSIDERITE).

The most conspicuous and most universally distributed mineral of the cavities is the siderite, which first attracted attention to the minerals here described. While siderite in the ordinary cleavable granular form is a common enough mineral, that in the basalt cavities is the variety which, on account of its peculiar concretionary form, is known as sphaerosiderite. Careful study of the specimens at hand



FIGS. 9-12.—SIDERITE FROM SPOKANE 9, RADIAL FORM OF FIRST GENERATION SIDERITE. 10, COMMON "TRIGONAL HOUR-GLASS" FORM OF FIRST GENERATION SIDERITE. 11, CURVED CRYSTAL OF SECOND GENERATION SIDERITE. 12, CRYSTAL DRAWINGS IN ORTHOGRAPHIC AND CLINOGRAPHIC PROJECTIONS OF CRYSTAL OF SIDERITE.

indicates that the siderite is of two distinct generations separated by iron opal. These may conveniently be considered separately.

The siderite of the first generation is widely distributed on the perfectly fresh nonopalized basalt, where it occurs always in small bodies more or less thickly scattered over the plagioclase crust. In size these range from very minute up to perhaps a maximum diameter of 3 mm. In color they are light yellowish to pistachio green, and they are nearly opaque with a waxy to velvety luster. Many of these siderite masses are almost perfect spherulites or aggregates of the same, but a great number also has a peculiar trigonal hour-glass form, in general resembling that shown in the drawing, figure 10. Occasionally some of these are bronze brown externally and beautifully iridescent, apparently from very slight surface alterations.

The second generation siderite, as contrasted with that of the first generation, occurs much more abundantly in its specimens and as much larger masses, the individual spheroids reaching an extreme observed diameter of 4 cm. It is much more translucent than the early variety and has a darker olive-green color. This siderite of the later generation is always, so far as seen, deposited in cavities in the rock which is dark colored by reason of having undergone opalization, and the siderite in the cavities is practically always underlain by a thin film of the ferric opal.

A cavity may contain only a single globe of siderite, or it may be almost completely filled with crowded units (pl. 2). Not infrequently the spherulites have grown in linear arrangement and by their union have produced peculiar caterpillarlike forms, as shown in plate 2, lower. The surfaces of these dark-colored second-generation nodules of siderite are usually velvety in appearance or in some cases remarkably and beautifully iridescent. Chance fractures show the nodules to have a radiate fibrous internal structure, although this is masked in most cases by the perfect rhombohedral cleavage of the mineral, yielding curved cleavage surfaces. Cross sections of the spheres when examined in polarized light show a homogeneous radiate fibrous structure in which individual fibers are so minute as to be indistinguishable. Between crossed nicols the nodules do not extinguish, but yield the dark extinction cross characteristic of very finely fibrous spherules. There is no indication of concentric structure indicating periodic growth or interrupted deposition of the siderite, nor are there any inclusions in the section, although one sample analyzed was found to include a flake of hyalite, though its surfaces were entirely cleavages. The optical properties of a nodule of second-generation siderite were determined by Larsen, who found the indices of refraction to be $\omega = 1.851$ and $\epsilon = 1.612$.

Four analyses of the Spokane siderite have been made with the results tabulated below:

Analyses of sphaerosiderite from Spokane.

	1	2	3	4
FeCO ₃	93.49	91.96	92.41	93.35
MnCO ₃	Trace.	.70	1.43	.73
CaCO ₃	5.13	5.51	3.74	3.13
MgCO ₃	1.83	2.53	3.10	3.00
Total.....	100.45	100.70	100.68	100.21

- (1) Analysis by J. P. Maider, city chemist of Spokane, probably second generation.
- (2) Average of two analyses by the writer made upon a second-generation nodule 1 cm. in diameter from which a thin section was cut.
- (3) Analysis by the writer on second-generation nodule 2 cm. in diameter.
- (4) Analysis by the writer of several small spherules of the light-colored first-generation siderite.

As shown by these analyses the material is ferrous carbonate with minor amounts of lime and magnesium carbonates and a very little manganese carbonate. The variation in composition from cavity to cavity is slight, and there is no essential difference in composition between the siderite of the first and second generations.

In only one specimen were simple crystals of the siderite found. These were yellowish translucent unit or cleavage rhombohedrons showing only the form r (10 $\bar{1}$ 1), as shown in sketch in figure 11 and in orthographic and clinographic projection in figure 12. These crystals, which averaged 2 mm. in diameter, occur scattered over the brown opal layer between nodules of ordinary second-generation sphaerosiderite.

In one specimen only is there evidence of a third growth of siderite, although the crystals noted above may belong to a period of deposition later than that of the second-generation nodules. In the specimen mentioned a cavity contains a dozen spheres of ordinary second-generation sphaerosiderite averaging 6 mm. in diameter, which rest, as usual, upon the brown opal crust. Coating the exterior of these spheres and evidently a later growth is a crust, 0.75 mm. in average thickness, of crystalline siderite made up of innumerable closely crowded rhombohedral crystals one-fourth mm. in diameter. The crystal crust is loosely attached to the earlier nodules and can be easily scaled off. The smooth surfaces of the original nodules are coated with a layer or film of rusty limonite, which looks as though some oxidation had taken place before the deposition of the crystal crust of the siderite. Scattered over the opal between the nodules are several typical saddle-shaped groups of small translucent brown rhombohedral siderite crystals.

The form of these siderites is that of typical sphaerosiderite. While botryoidal forms are not rare in other carbonates of the same group, being characteristic especially of smithsonite, these forms, for smithsonite at least, grade imperceptibly into the crystalline-rhombic modifications. Such botryoidal, mammillary, and spheroidal forms have been called colloform by Rogers¹⁷ because they are the forms assumed by colloids, which are devoid of any definite tendency to assume crystal form, and thus tend to form spheres. As has previously been pointed out, minerals form spherical bodies because they were deposited first as colloids and have retained the colloidal form after crystallization. As perhaps the most typical example of this process chalcedony may be mentioned. This mineral, though now crystalline, owes its form undoubtedly to its being originally deposited as opal, and the rearrangement during crystallization has not been sufficient to destroy the original form. On the other hand, some minerals form spherical bodies when deposited in crystal-

¹⁷ Austin F. Rogers. A review of the amorphous minerals. Journ. of Geol., vol. 25, 1917, p. 514.

line form by reason that a large number of crystal units started growth in a narrow space, and the mutual interference during growth has compelled growth to take place all in one direction, resulting in radial-fibrous spherical bodies. The exteriors of such bodies are usually covered with euhedral terminations of the crystals making up the spherical mass. A study of the Spokane siderites from this standpoint leads to the conclusion that the iron carbonate was in colloidal form when deposited, a conclusion sustained by the perfectly spherical form taken by a majority of the nodules, their entire homogeneity, lack of concentric rings, fineness of fibrous structure, and the absence of crystal terminations on their exterior. On the other hand, the apparently third-generation drusy crust on the siderites of one nodule was doubtless deposited in crystalline form.

The sphaerosiderite variety of iron carbonate is known from a number of localities in Europe, but no previous locality comparable to these European occurrences has been found in the United States. At Felsobanya in Hungary typical spherical bodies of siderite occur in veins with ore minerals, but the typical European occurrences are, like the one at Spokane, in vesicles in basaltic rocks. A specimen in the National Museum from Steinheim, Hesse, Germany (Cat. 78,837), is so similar to those from Spokane as to be indistinguishable without microscopic examination of the enclosing rock.

FERRICALCITE.

One specimen, which when received was labeled "Pseudomorph after siderite," consists of the dark-colored opalized rock containing a cavity of the usual type lined with the ferric opal. In this cavity is a single roughly spherical nodule about 17 mm. in diameter, which has a light buff color and velvety surface. When fractured, the interior is white, compact, dense-fibrous, and tough. Fragments dissolve quickly with effervescence in cold dilute hydrochloric acid. Upon standing in the air fresh surfaces begin to turn buff immediately. C. S. Ross, upon microscopic examination found this material to have optical properties intermediate between those of calcite and siderite, and it is evidently an intermediate lime-iron carbonate. It is not probable that this represents a replacement of an original siderite nodule, but it more probably represents local variation in the composition of the carbonate-depositing solutions. It is possible that it represents an outer deposit and that a nodule of the ordinary siderite is enclosed within the ferriferous calcite nodule; but this could not be determined without destroying the specimen, which is the property of the Eastern Washington State Museum.

OPAL.

At least two varieties of opal are abundantly present in the specimens. The first of these, which has been referred to as iron opal,

occurs throughout the cavities which contain the large second-generation siderites as a thin botryoidal layer underlying the siderite. It also occurs interstitially in the enclosing rock, constituting a particular and typical form of alteration or opalization. In the hand specimen this opal is dark brown to black in color with greasy, pitchy, or velvety dull luster. Under a lens it is seen to have a minute botryoidal surface. It coats the earlier minerals, feldspar, magnetite, cristobalite, and first-generation siderite. The dark-brown color is doubtless due to ferric hydrate, indicating that the opal was formed in the presence of free oxygen; but the solutions which deposited it in the cavities were not oxidizing, since the minute siderite globules beneath the opal layer are not oxidized. Under the microscope the opal is transparent, reddish brown to golden brown in color, and devoid of any cleavage or inclusions. It is completely isotropic with an index of refraction of 1.445 ± 0.003 . The material varies somewhat in index, however, that in the fabric of the basalt running down as low as 1.432 ± 0.003 .

The second variety of opal is perfectly limpid colorless hyalite which was deposited later than the second-generation siderite, although it is not confined to the cavities containing this siderite, but sometimes coats first-generation siderite in nonopalized light-colored basalt. Its perfectly limpid transparent botryoidal crusts vary from exceedingly thin to a thickness of 3 mm. or more (pl. 3, upper). It may occur coating the entire interior of a cavity, being deposited impartially on all of the minerals, or it may be dotted in minute limpid drops over the surfaces of the siderite. In one or two specimens the hyalite appears to be earlier than the second-generation siderite, but this is due apparently to its depositing over the space between the siderites and avoiding them. The opal is later than the aragonite in the single specimen in which both occur, and long acicular aragonite crystals bear a bead of hyalite at their termination. Under the microscope the hyalite is transparent and colorless. It is feebly birefringent and has an index of refraction of 1.455 ± 0.003 .

ARAGONITE.

Aragonite occurs as a constituent of two specimens. One of these is a rosette of long prismatic crystals of aragonite, which shows no basalt attached, nor does it show any of the other characteristic minerals, so that its relationships are not known. The crystals are repeatedly twinned and have obscure terminations resembling fractures. Little could be learned from a crystallographic study. The second specimen shows aragonite in minute acicular crystals and crystalline masses resting on iron opal in a cavity in black vitreous basalt. The aragonite is partly coated by hyalite. The crystals are too minute and imperfect for measurement.

CALCITE.

Calcite was noted only once as a snow-white nodule in a cavity in rather dense basalt from the Spokane River at Wall Street. The snow-white nodule rested lightly on several chain aggregates of second-generation siderite. The interior structure of the nodule was radial-fibrous, and it was very friable, the fibers separating readily. It was readily soluble in cold dilute acid. Measurement of the indices of refraction showed that this carbonate was calcite rather than aragonite. While the exterior of the nodule bristled with minute terminations, these were etched dull and no measurements could be made.

BARITE.

Barite occurs in only one specimen, where it is abundant as a crust of acicular colorless crystals up to 2 mm. in length. It is associated with both second-generation siderite and hyalite, and although it is later than both of these it has deposited between them on the lining of the cavity in preference to resting on either. Under a lens the barite resembles quartz to a remarkable degree. Under the microscope crystals resting on a tabular face of *c* (001) show the emergence of the obtuse bisectrix, and well-defined cleavage parallel to *m* (110). The orientation adopted in the drawings gives optical orientation in agreement with the data given for barite, while one index on such a section is higher and one is lower than 1.640. The resemblance to quartz crystals is heightened by tapering of the crystals, this distortion amounting to 10° or more, as shown in the drawing, figure 13. The most highly modified crystal seen had the development shown in figure 14. The smaller faces are very minute and give very faint signals, while the distortion mentioned affects the angles. The measurements obtained on the crystal (fig. 14), are given below:

Forms and angles of barite crystal from Spokane.

Letter.	Miller.	Reflection, etc.	Measured.		Calculated.	
			φ		ρ	
			$\circ$	$'$	$\circ$	$'$
<i>c</i>	001	Very good.....	..	..	0	00
<i>b</i>	010	Bright narrow line.....	0	07	90	00
<i>m</i>	110	Very good.....	50	49	90	00
<i>η</i>	320	Very minute, no signal.....	59	06	90	00
<i>λ</i>	210	Small but bright.....	68	29	90	00
<i>o</i>	011	Blurred, distorted.....	5	00	52	40
<i>u</i>	101	Very faint, minute.....	88	08	61	26
<i>d</i>	102	Very good.....	89	33	39	01
<i>W</i>	108	Poor, rounded.....	88	16	12	51
<i>z</i>	111	Good.....	50	52	64	20
<i>y</i>	122	Minute, faint.....	28	54	56	44
<i>ρ</i>	144	Very poor, minute, rounded..	17	13	53	39
<i>R</i>	223	Very poor, no signal.....	49	29	53	08
					50	49
					54	11

LIMONITE AND GOETHITE.

It remains only to describe the minerals formed by the alteration of the siderite under the influence of weathering, the ferrous carbonate being converted readily upon exposure to the hydrated ferric oxides limonite and goethite. These minerals form perfect pseudomorphs after the original siderite nodules, the oxidation having been accomplished with no alteration in volume. The limonite-goethite pseudomorphs are firm and hard, and thin sections and polished

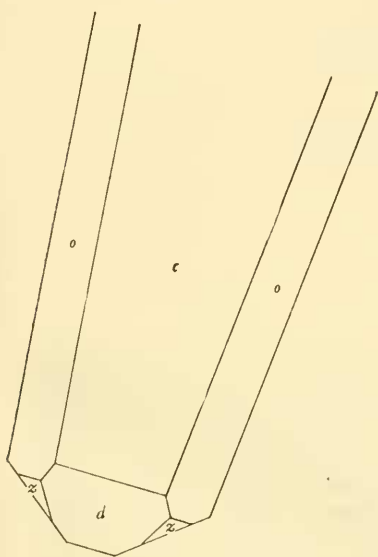


FIG. 13.—BARITE CRYSTAL FROM BASALT. SIMPLE CRYSTAL SHOWING TAPERING.

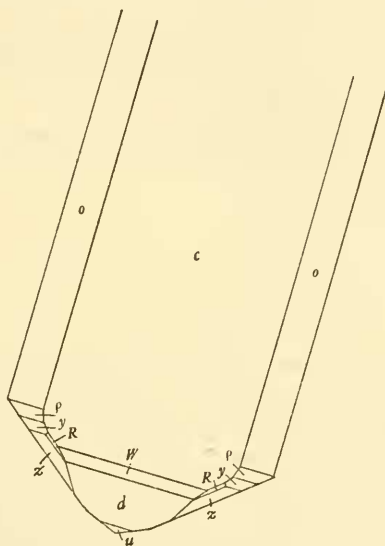
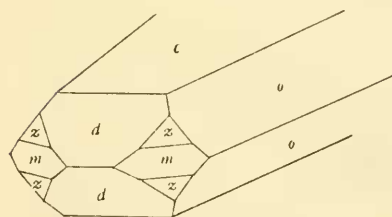


FIG. 14.—BARITE CRYSTAL SHOWING 13 FORMS. FROM BASALT.



cross sections show them to preserve the internal structure of the siderite, the pseudomorphs being radially fibrous. The fibers are composed of crystalline goethite, while amorphous limonite occurs interstitially between the goethite fibers. The exteriors of the nodules of oxidized siderite are often smooth and glossy. In no case was a nodule seen only partly oxidized or with a core of unaltered siderite, the alteration apparently proceeding very rapidly under oxidizing conditions. In one specimen containing several cavities, in which were numerous small nodules of first-generation siderite, the

siderites of one cavity were entirely oxidized while all of those of the other cavities were perfectly fresh.

PARAGENESIS AND DISCUSSION.

To summarize, the basalt cavities contain several minerals, which, beginning with the first, may be listed in the order of their deposition as follows:

1. Plagioclase, crystals and enamelliform.
2. Magnetite.
3. Cristobalite.
4. Siderite (sphaerosiderite), first generation.
5. Pyrite.
6. Iron opal.
7. Siderite (sphaerosiderite), second generation.
8. Ferralcite.
9. Calcite.
10. Aragonite.
11. Hyalite.
12. Barite.
13. Goethite.
14. Limonite.

When one comes to assign a source to these several minerals, there develop difficulties in the shape of insufficient data, and opinions must be largely speculative. There can exist little doubt that the feldspar, magnetite, and cristobalite are high-temperature deposits formed in the cavities while the basalt was at an elevated temperature and very soon after its consolidation. Careful consideration has led to the conviction that the small spherulites of first-generation siderite are likewise intimately related to the cooling of the lava, although this mineral was probably formed at a somewhat lower temperature than the preceding ones. The pyrite, in view of its universal distribution and the fact that it does not occur in quantity, may be glossed over without discussion. With the iron opal, however, difficulties again become paramount. There is to be considered not only the film of this opal in the cavities but that which is developed in the enclosing rock, constituting a unique type of alteration, opalization, of the basalt. That this opal is colored by ferric oxide indicates that it was formed, or at least colored, in the presence of available oxygen. The opalization is a local phenomenon, as is the presence of second-generation siderite in the cavities, the two being coextensive. For the present it will be sufficient to remark that the opal has the appearance of a percolating water deposit, and its source may be connected with the underlying fine-grained silt. The same agency which deposited the opal doubtless also deposited the second-generation sphaerosiderite, and it is not improbable that this latter represents a concentration, by solutions, into favorable

situations of the original or first-generation siderite from over a much wider area. Some change must have taken place in the solutions, since it is difficult to conceive solutions depositing ferric-iron opal and ferrous carbonate under the same conditions. The other minerals, aside from the hyalite, are very local and more or less adventive substances whose source must remain problematic. The limonite and goethite are distinct from the other minerals in that they are products of ordinary weathering.